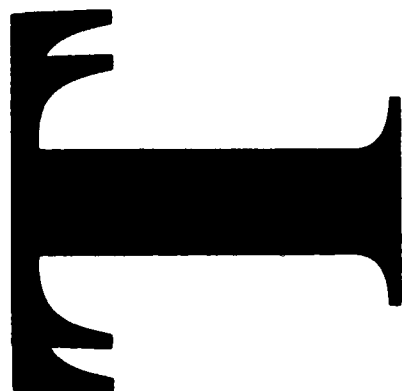
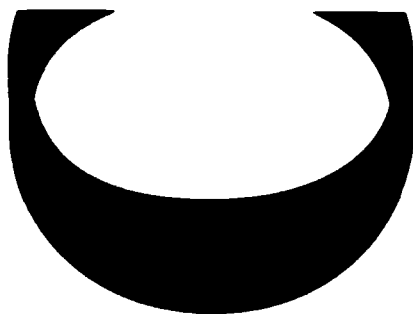


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# An Overview of Aircraft Integrated Control Technology

G.J. Simpkin

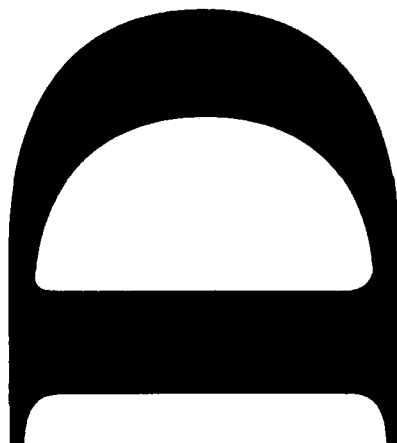
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# An Overview of Aircraft Integrated Control Technology

*G. J. Simpkin*

Air Operations Division  
Aeronautical and Maritime Research Laboratory

DSTO-GD-0013

## ABSTRACT

Integration of flight control systems with other aircraft subsystems has been shown to significantly enhance the ability of aircraft to achieve mission goals. This report examines the scope and current status of aircraft integrated control technology, through an overview of research programs which have developed Integrated Flight and Propulsion Control (IFPC) systems, Integrated Flight and Fire Control (IFFC) systems, and enabling technologies. Trends observed within integrated control are commented on, and some suggestions are made regarding future DSTO involvement in this field.

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# **An Overview of Aircraft Integrated Control Technology**

## **EXECUTIVE SUMMARY**

Modern military aircraft incorporate a number of complex subsystems, such as avionics, fire control, propulsion, navigation, countermeasures and flight control. Traditionally, the control laws developed for most controllers have been designed independently, without taking into account interactions which may occur between subsystems. Aircraft integrated control technology is enabling the design of control laws which take subsystem interactions into account.

As an example, consider the integration of propulsion control and countermeasure control subsystems. An integrated control system might respond to a heat-seeking missile threat by modulating the infrared signature of the engine exhaust plume while simultaneously ejecting infrared decoy flares. In this example, the integrated control system would be working to optimise the likelihood of avoiding the heat-seeking missile.

Flight test and simulation studies have shown that even partial integration of aircraft subsystems can offer the following benefits:

- performance improvements;
- enhanced survivability;
- improvements in flight safety and availability;
- optimised pilot workload; and
- reduced life cycle costs.

This document presents an overview of aircraft integrated control technology. As the scope of integrated control is broad, no attempt is made to explore integrated control developments in detail. Instead, the concept of integrated control is discussed, and developments in integrated control technology are outlined through accounts of unclassified research programs. The report concludes by speculating upon the future application of integrated control within aircraft, and makes some recommendations regarding further DSTO involvement in this field.

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**ACKNOWLEDGEMENTS**

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## 1. INTRODUCTION

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The integration of flight control systems with other aircraft subsystems (such as the propulsion control system or the fire control system) has been shown to dramatically improve aircraft combat performance<sup>1,2,3</sup>. Benefits arising from integrated flight control include:

- enhanced survivability;
- improvements in flight safety and availability;
- reduced life cycle costs;
- performance improvements; and
- optimised pilot workload.

This report has been compiled to develop awareness of the scope of recent developments in integrated control systems within aircraft. The concept of integrated control is defined, and unclassified accounts of research programs, which are instrumental in the development of current technology thrusts, are discussed. The report concludes with some speculation about where technology trends are leading, and suggests possible avenues for further investigation within DSTO.

## 2. DEFINING INTEGRATED CONTROL FOR AIRCRAFT

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Before attempting to define the concept of functionally integrated control, it may be of benefit to provide an example.

Consider an air-to-air gunnery scenario\*. Aircraft currently in service employ either a lead computing optical sight (LCOS) or director radar fire control system to provide fire control solutions to the pilot<sup>4,5</sup> during an aerial engagement. The pilot manoeuvres the aircraft to bring the gun to bear on the target, according to the computed fire control solution displayed on the head up display (HUD). Because there is no direct link between the fire control system and the flight control system, it is the pilot who performs the integration between the two systems.

At its most basic level, the functional integration of the flight control system and the fire control system would imply the sharing of information between the systems to achieve a mission goal. For the scenario described, one concept which has been demonstrated is that of the IFFC-1/FIREFLY III project<sup>1</sup> which closed the loop between fire control and flight control systems to achieve automatic engagement of the target. In using the fire control director to supply outer loop demands to the flight control system, a fundamental building block for integrated fire and flight control was developed.

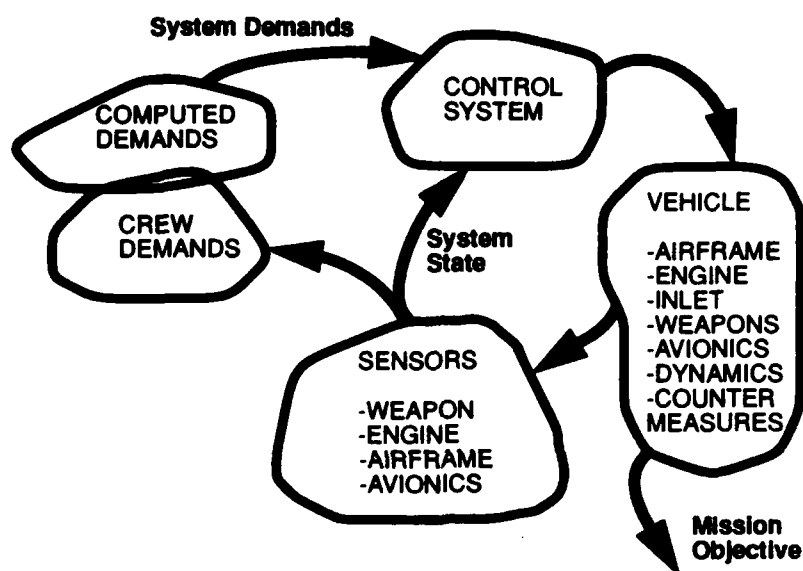
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\*. The topic of air-to-air gunnery is discussed in greater detail in section 3.2

### 3. INTEGRATED CONTROL DEVELOPMENTS

Schwanz et al.<sup>6</sup> suggested that the key to recognising functional integration is the realisation that the dynamics of the subsystem components (of the vehicle) are interdependent. Thus, for the purposes of this paper, the phrase 'integrated control' may be taken to imply control system design which takes into account the interactions between the subsystems. Ideally, such a control system will be designed to manipulate variables in all relevant subsystems so that the vehicle can achieve a desired mission objective. This is illustrated in Figure 1.

FIGURE 1. Functionally integrated control concept



Subsystems which have been considered for integrated control applications include airframe, propulsion, cockpit, navigation, weapon and countermeasure systems. Thus the scope of integrated control technology is as broad as the system technologies which make up modern military aircraft.

### 3. INTEGRATED CONTROL DEVELOPMENTS

Functional integrated control has been undergoing development since the early 1970s. During that period, most research and development programs on this topic have been restricted to the integration of the flight control system with one other major subsystem due to task complexity and risk<sup>7</sup>. Research and development programs directed toward the integration of flight control systems with propulsion control and fire control systems have been documented extensively in published literature. These programs are discussed in the

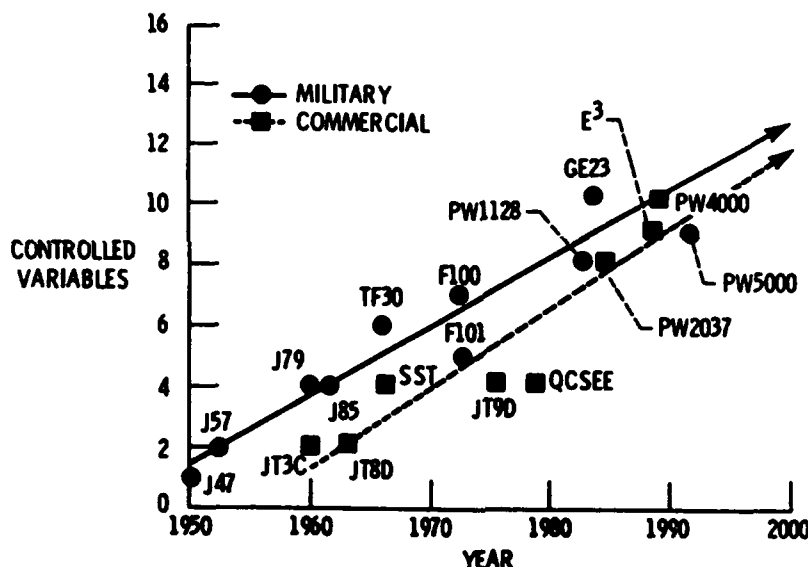
### 3. INTEGRATED CONTROL DEVELOPMENTS

following text. Other integrated control issues, such as the integration of flight control systems with navigation subsystems, are discussed under in section 3.3, 'Enabling Technologies'.

#### 3.1 Integrated Flight and Propulsion Control

Integrated Flight and Propulsion Control (IFPC) systems have received particular emphasis for two reasons. Firstly, as noted by Lorenzo<sup>8</sup>, the complexity of airbreathing engines, as indicated by the number of controllable variables, has steadily increased over the years (Figure 2). In an increasingly complex operational environment, it is expected that acceptable mission performance will only be achieved if pilot workload is reduced\* using integrated control technology<sup>9</sup>.

FIGURE 2. Trends in aircraft turbine engine complexity (from Ref. 8)



Secondly, as noted by Mihaloew<sup>10</sup>, the large degree of dynamic cross coupling that exists between the airframe and propulsion subsystems (especially with V/STOL aircraft) provides another important impetus for integrating flight and propulsion control systems. Both of these issues are discussed in the program descriptions which follow.

\*. It is not expected that integrated control technology will be used to reduce every demand placed on the pilot. Under some conditions, for example when pilot workload is low, a reduction in workload may actually lead to a decrease in pilot performance. Combat related aircraft missions, however, can create high pilot workloads, to the point of overloading the pilot and reducing his/her capability for completing mission critical tasks. It is these peaks in pilot workload which may be reduced by using integrated control technology.



#### **Integrated Propulsion Control System**

The joint United States Air Force (USAF) and National Aeronautics and Space Administration (NASA) Integrated Propulsion Control System (IPCS) program was implemented on an F-111E long range fighter-bomber research aircraft in the mid-1970s<sup>3</sup>. The variable geometry inlet and engine were integrated using a full authority digital engine control system for controlling inlet shock and automatic restart. Amongst the benefits demonstrated were increased thrust, increased range, faster throttle response and stall-free engine performance.

#### **Cooperative Airframe-Propulsion-Control System**

In the late 1970s, the NASA YF-12C aircraft (Figure 3) was used to conduct research into the integration of inlet control, autothrottle, airdata and navigation systems. Prior to the application of integrated control, the aircraft exhibited strong interactions between the airframe and the propulsion system, which impaired both the longitudinal and lateral directional characteristics of the aircraft. Analysis of flight test results concluded that the engine inlet geometry had the same order of control effectiveness on lateral stability as did the ailerons and rudders.

**FIGURE 3. The NASA YF-12C research aircraft (taken from Ref. 3)**



Burcham, Gilyard and Myers<sup>11</sup> summarised the step by step integration program implemented on the YF-12C, which resulted in improved altitude control capability and range improvements of 5 percent. The technology was subsequently incorporated into the SR-71 fleet as part of a major avionics upgrade which realised a 7 percent

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### 3. INTEGRATED CONTROL DEVELOPMENTS

range improvement and eliminated the sudden relocation of the inlet compression shock system known as 'inlet unstarts'.

#### **F-15 HIDEDEC**

The Highly Integrated Digital Engine Control (HIDEDEC) program carried out by NASA focused on the integration of engine, flight and inlet control systems in an F-15 research aircraft. Early HIDEDEC goals were based on the recommendations of another NASA study titled Integrated Research Aircraft Technology (INTERACT)<sup>12</sup>. Following the successful demonstration of preliminary program goals, the F-15 HIDEDEC facility was used to investigate other IFPC technologies, including Self-Repairing Flight Control Systems, Performance Seeking Control and propulsive techniques for emergency flight control.

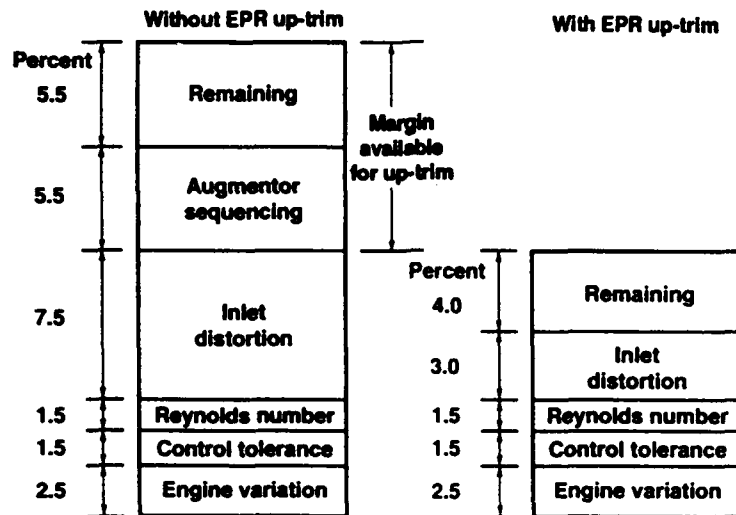
The F-15 research aircraft was fitted with both a Digital Electronic Flight Control System (DEFCS) and a Digital Electronic Engine Control (DEEC) specially developed to enable control system integration. The DEEC is a full-authority, engine mounted digital system that performs the functions of the standard F100 engine hydro-mechanical control system<sup>13</sup>. DEEC inputs include power control lever angle, Mach number, fan inlet static pressure, burner pressure, turbine discharge total pressure, fan inlet total temperature, turbine inlet temperature, rotor speed sensors, and feedback from numerous actuators. The DEEC system uses those inputs to control variable compressor vane angles, compressor bleeds, gas generator and augmentor fuel flows, and exhaust nozzle area. Even without flight control system integration, the DEEC demonstrated major improvements in engine reliability and maintainability over the standard F100-PW-100 control system. NASA conducted a study showing that \$150 million US (1983) savings through aircraft maintenance could result from implementation of DEEC on one-half of the US F-16 fleet<sup>13</sup>. As a result, the DEEC went into production on the derivative F100-PW-220 engine in 1986.

#### **F-15 HIDEDEC ADECS**

Of the six control modes evaluated by the INTERACT program, the mode predicted to provide the largest engine performance improvement was the Adaptive Stall Margin (ASM) mode.

Conventional engine control systems apply a stall margin to the engine pressure ratio (EPR) operating envelope to account for worst case flight and engine disturbances. The Advanced Engine Control System (ADECS), developed on the recommendations of the INTERACT program, reduces the stall margin in real time to the amount required for the prevailing flight and engine conditions. Figure 4 illustrates the stall margin reductions obtained by up-trimming (increasing) the EPR.

FIGURE 4. EPR Stall Margin Reductions (from Ref. 14)



Flight testing of ADECS demonstrated that EPR up-trim could be used to increase thrust by up to 10.5 percent for an intermediate power setting. Alternatively, the up-trim could be used to reduce thrust specific fuel consumption (TSFC) by up to 16 percent whilst maintaining constant thrust. An extended engine life mode was implemented, and was shown to reduce turbine temperatures by up to 80°F (45°C). The engine manufacturer predicted that the temperature reduction would result in an increase of turbine life by 10 to 15 percent<sup>15</sup>. ADECS technology has been implemented on the F100-PW-229 and other advanced engines<sup>11</sup> as a result of the HIDECS research.

### SRFCS

The Self-Repairing Flight Control System (SRFCS) program was initiated by the USAF in the early 1980s. Program objectives were to improve aircraft reliability, maintainability, survivability and life cycle cost through real-time control system reconfiguration and onboard maintenance diagnostics. Preliminary studies highlighted the following key SRFCS functions<sup>16</sup> for development:

- system impairment detection and classification;
- control surface reconfiguration;
- positive, real-time, pilot alert; and
- onboard maintenance diagnostics.

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### 3. INTEGRATED CONTROL DEVELOPMENTS

Should a control surface become inoperable (for example due to battle damage), the SRFCS would identify the fault and reconfigure the control system to compensate using the remaining control effectors. After reconfiguring the control system, a Positive Pilot Alert system would alert the pilot to the impairment and inform him/her about new performance limitations. The combination of these technologies enables the pilot to retain control of the aircraft following control system failures which might otherwise have rendered the aircraft inoperable.

Onboard maintenance diagnostics would monitor system operation during flight and, using an expert system, diagnose FCS faults to assist ground maintenance engineers. In this way, faults which potentially might not be reproducible on the ground can be dealt with quickly, thus reducing cost and increasing aircraft availability.

Two major components of the SRFCS research were the Control Reconfigurable Combat Aircraft (CRCA) design study and CRCA piloted aircraft simulation, which was conducted to develop reconfiguration strategies for incorporation into the Advanced Tactical Fighter (ATF) program<sup>17</sup>. The technologies developed were flight tested on the HIDEF F-15 research aircraft<sup>18</sup>, demonstrating for the first time the successful application of the four key SRFCS technologies on a fighter aircraft.

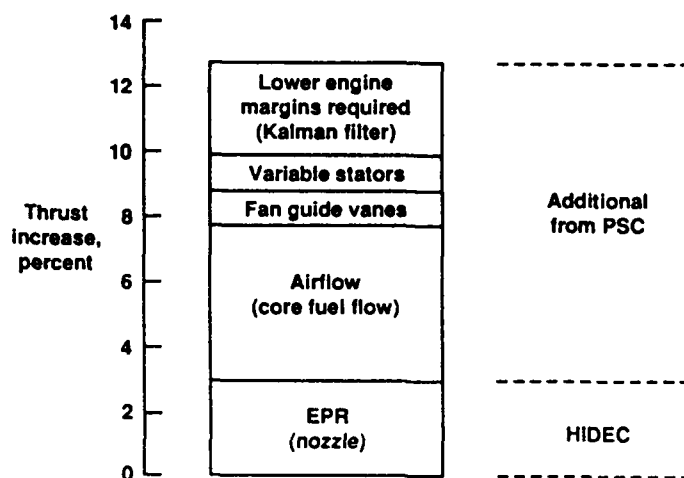
A follow-on study, entitled Advanced SRFCS, was scheduled for the early 1990s to focus the technology on applications other than ATF, including F-15 and F-16 upgrades, and close air support vehicles<sup>17</sup>.

#### **F-15 HIDEF PSC**

The Performance Seeking Control (PSC) program, which was implemented by NASA, builds upon the performance improvements offered by ADECS. The ADECS control schedules were calculated off-line using assumed 'normal' engine parameters. PSC achieves an additional benefit by optimising the control algorithm for actual in-flight engine conditions.

Standard engine sensor information is input through a Kalman filter to adaptively tune an engine model, thus matching it to the conditions of the actual engine. The engine model is then used in conjunction with a linear-programming algorithm to optimise the selected performance objective. Figure 5 shows a breakdown of the thrust increase attributable to PSC for a particular flight condition.

**FIGURE 5. PSC thrust increase breakdown (from Ref. 11)**



The PSC optimisation algorithm has three modes:

- maximum thrust mode which maximises thrust minus drag;
- minimum fuel mode which minimises fuel consumption during cruise; and
- minimum fan turbine inlet temperature mode which extends engine life by reducing turbine wear rate.

Flight tests performed with the HIDEDEC F-15 research aircraft showed that thrust increases of up to 15 percent, or reductions in turbine temperature of more than 160°F (90°C) can be achieved using PSC algorithms.

#### **F-15 HIDEDEC PROTECT**

Research has shown that the flight path of most multi-engine aircraft can be controlled by modulating engine thrust to produce changes in pitch and yaw/roll angles. A NASA research program has used piloted simulations of several multi-engine aircraft to evaluate the potential for using PROpulsive Techniques for Emergency ConTrol (PROTECT) as a means of recovering from catastrophic control system failures<sup>19</sup>. Results from that program showed that it is very difficult to achieve precise control with manual throttle commands, because of the lag in flight path response to throttle changes and phugoid (long period longitudinal oscillation) characteristics of the aircraft.

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### 3. INTEGRATED CONTROL DEVELOPMENTS

An augmented control system was developed so that the pilot could control pitch and yaw through autopilot-like thumb-wheel controls. The system converts the pilot's pitch and yaw inputs into appropriate engine throttle demands, thus damping out phugoid motion and improving flying qualities to the point where they are acceptable for emergency landings.

The HIDEF F-15 research aircraft demonstrated the potential of the PROTECT system after it successfully completed a mock-emergency landing mission under engines-only control in April 1993.

#### **F/A-18 HARV**

A standard F/A-18 aircraft has been equipped with simple thrust-vectoring vanes and an experimental research flight control system, developed by NASA, under the High Angle-of-Attack Research Vehicle (HARV) program. The F/A-18 HARV has been used to investigate means of expanding the control authority envelope to produce improved fuselage pointing characteristics. Fuselage pointing, or the ability to point an aircraft fuselage at an adversary\* during aerial combat, is rapidly becoming desirable as a modern combat manoeuvre.

The F/A-18 HARV, which integrates thrust-vectoring with aerodynamic controls in a manner that is transparent to the pilot, underwent initial flight tests using the thrust vectoring system in July 1991. Subsequent flight tests demonstrated a significant improvement in roll performance for angles-of-attack greater than  $20^\circ$ , and adequate control authority for angles-of-attack of up to  $70^\circ$  during symmetrical manoeuvres<sup>20</sup>. Additional experiments, designed to evaluate new control laws (which were developed using modern control theory) and actuated strakes mounted on the forebody, are expected to be carried out during 1994.

#### **VAAC**

Flight control research into advanced VSTOL aircraft has been undertaken by the Defence Research Agency, Farnborough, through the Vectored thrust Aircraft Advanced flight Control (VAAC) program which was initiated in 1983. Program aims are to develop and validate a range of flight control concepts (control laws, inceptors and display formats) and new design and assessment techniques. VAAC findings are expected to contribute to the technology base for complex VSTOL systems and thus to IFPC. A two-seat Harrier aircraft has been modified for flight testing of the control strategies<sup>21</sup>.

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\*. Or, more precisely, the goal of fuselage pointing is not to point the fuselage directly at an adversary, but to point the fuselage in the direction for which fire control solutions have been calculated when attacking that adversary.

#### F-15 S/MTD

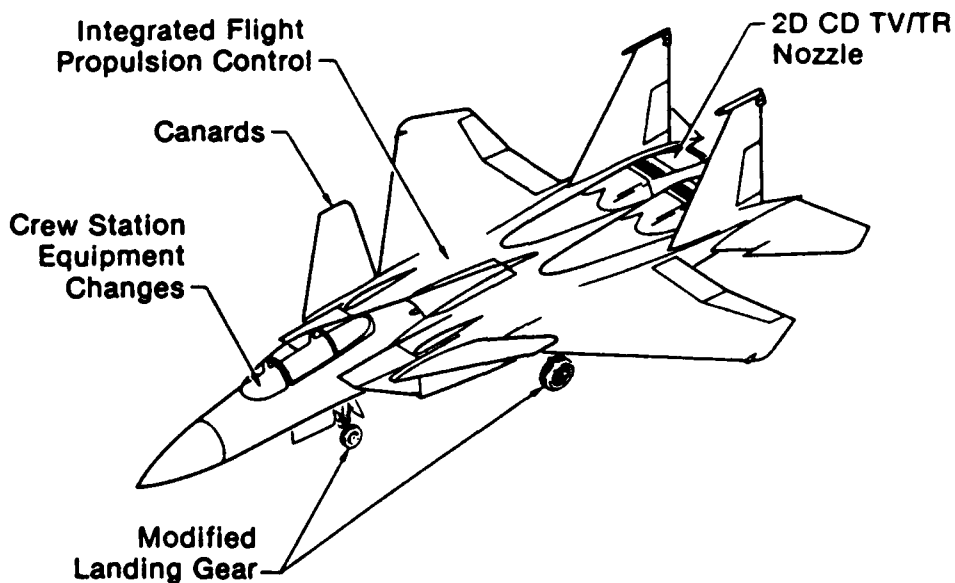
The McDonnell Aircraft Company, under contract to the USAF, has conducted a STOL Maneuver Technology Demonstrator (S/MTD) program to develop and test four technologies so that they may be more easily transitioned into current and future combat aircraft. The four technologies to be tested were:

- two dimensional thrust vectoring and reversing exhaust nozzle;
- Integrated Flight Propulsion Control (IFPC) system;
- Pilot-Vehicle Interface (PVI); and
- rough/soft field landing gear.

Performance goals for the program included short airfield operations (less than 1500 ft or 458 m) under adverse weather conditions while maintaining superior flying qualities (in performance and handling) throughout the flight envelope.

The primary requirement of the IFPC system was that it be "capable of functionally integrating all aspects of flight, engine, and nozzle control, including aerodynamic control surfaces, engine thrust, thrust vectoring, thrust reversing and differential efflux modulation, control and stability augmentation, high lift system, steering and braking<sup>22</sup>". An F-15B research aircraft, modified with all-moving canard control surfaces (see Figure 6), completed three years of flight testing in August 1991.

**FIGURE 6. S/MTD F-15 configuration (from Ref. 23)**



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### 3. INTEGRATED CONTROL DEVELOPMENTS

All four technology developments were successfully demonstrated. Flight test highlights included the following<sup>24</sup>.

- Runway takeoff length was reduced by 38 percent.
- The autonomous landing guidance system technology (improved PVI) was tested and subsequently transitioned into the USAF TAC F-15E fleet.
- In-flight thrust reversal was demonstrated at speeds of up to Mach 1.6. It was found that thrust reversal can slow the aircraft down to its corner velocity more quickly than by using a speed brake. (The corner velocity represents the best airspeed for manoeuvring during aerial combat.)
- S/MTD pitch response at 30° angle-of-attack was doubled through the use of thrust-vectoring.

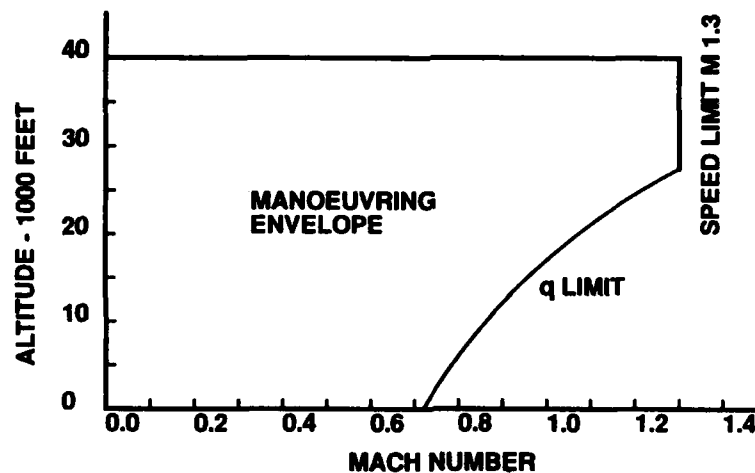
#### **Supermanoeuvrability and X-31**

Chin<sup>25</sup> defined supermanoeuvrability (super-M) as manoeuvring with very high levels of agility and controllability. Agility refers to the ability of an aircraft to make rapid transitions from one energy state to another, and controllability refers to the ability to change the aircraft velocity vector and nose attitude, rapidly, for any flight condition. Integrated control is an enabling technology for super-M aircraft because the need for precise control across a broad range of flight conditions implies the integrated use of numerous control effectors.

A single seat combat aircraft, the X-31A, has been jointly developed by Rockwell International (USA) and Deutsche Aerospace - MBB (Germany) to investigate post stall manoeuvring (a super-M concept) as a means of enhancing fighter combat performance. Program participants include the US Defense Advanced Research Projects Agency (DARPA), USN, USAF, and the German Ministry of Defence. Integrated control systems, thrust vectoring and pilot assistance are the primary techniques being applied to enhance aircraft agility within the expanded manoeuvre envelope shown in Figure 7.



**FIGURE 7. X-31A Flight envelope**



The IFPC system responds to pilot inputs with an automatic blend of aerodynamic control surfaces and thrust vectoring to provide precise control throughout high angle-of-attack manoeuvres. Good control responsiveness at low speeds is expected to endow the aircraft with excellent fuselage pointing capabilities. These will be evaluated for their tactical utility during flight testing.

Flight testing, which began in 1990, has demonstrated controlled flight at angles-of-attack up to  $70^\circ$ . Tactical utility flight tests are expected to begin in 1993<sup>20</sup>.

#### **MATV**

At the time of writing, the USAF plans to conduct some 100 hours of flight tests using an axisymmetric pitch/yaw nozzle under the MultiAxis Thrust Vectoring (MATV) program. The project will employ the USAF Variable stability In-flight Simulator Test Aircraft (VISTA) F-16 as a testbed to examine manoeuvrability and agility benefits offered by thrust vectoring<sup>26</sup>.

#### **ACTIVE**

NASA-Dryden will use the S/MTD F-15B research aircraft to evaluate trim drag reduction benefits which may be obtained by using axisymmetric pitch/yaw vectoring nozzles. Flight testing of Advanced Control Technology for Integrated Vehicles (ACTIVE) is expected to begin in September 1994. The experiments are expected to demonstrate trim drag reductions of at least a few percent<sup>26</sup> when using the vectoring nozzles to trim the aircraft instead of conventional aerodynamic surfaces.

#### **PACIR**

The USAF plans to capitalise on the technology developments of the MATV and ACTIVE programs by following up with the Propulsion, Aerodynamics, Controls Integration Research (PACIR) program. PACIR is planned to provide a full evaluation of the air-to-air and air-to-ground manoeuvrability and agility benefits offered by advanced thrust vectoring. Flight testing is expected to begin in 1996, and will explore the full flight envelope<sup>26</sup>, including applications to short-field takeoff and landing.

#### **MUSIC**

The Multi-System Integrated Control (MUSIC) program, planned by the USAF, will incorporate the results of many IFPC programs (DMICS, HIDE, PROLIFIC, INTERFACE, X-31, S/MTD, HARV and others) to demonstrate how IFPC may be used to improve combat effectiveness, reliability and maintainability while reducing aircraft observability<sup>7</sup>.

#### **STOVL**

IFPC technology has been highlighted as one of the most difficult issues to be resolved in the development of an advanced supersonic Short TakeOff Vertical Landing (STOVL) fighter/attack aircraft<sup>27</sup>. The high degree of dynamic coupling between the airframe and propulsion subsystems across a broad range of flight conditions, an increasing number of variables to be controlled within each subsystem, and the need to reduce control system mass while enhancing reliability<sup>8</sup> are all driving factors in the development of IFPC for STOVL applications.

Several research programs have been initiated in the US, the UK and Canada with the aim of jointly developing advanced supersonic STOVL capabilities for the post-ATF time frame. The US-UK cooperation has been largely carried out under the Advanced STOVL (ASTOVL) Common Technology Program Memorandum of Understanding (MOU). A similar agreement exists between the US and Canada. Research activities in this field have led to the possibility of a further MOU between the UK MoD and the US DoD for development of a STOVL Strike Fighter (SSF) which could enter service around 2010<sup>28</sup>.

### **3.2 Integrated Flight and Fire Control**

Coupling fire control information with the flight control system has been shown to increase weapon accuracy significantly in both air-to-air and air-to-surface roles. The ability to deliver weapons accurately (air-to-surface) whilst manoeuvring is expected to increase the survivability of the aircraft. Survivability should also be enhanced by increased situational awareness, which is made possible by reducing the high level of pilot workload, during Integrated Flight and Fire Control (IFFC) combat engagements. The

programs discussed below vary mostly in the level of automation applied to aircraft manoeuvres during each phase of combat.

#### **IFFC-I/Firefly III**

During the late 1970s, the General Electric company was contracted by the USAF to perform manned simulation studies on IFFC applications for the F-15, F-16 and A-10 aircraft. This program, known as FIREFLY II, demonstrated significant improvements in both tactical weapon delivery performance and survivability. As a result of this work, the USAF let two further contracts, IFFC-I and FIREFLY III, in order to test the validity of the remarkable simulation results through 15 months of flight testing on an F-15B testbed.

The IFFC-I/FIREFLY III program tested the fundamentals of IFFC. Target tracking errors were automatically nullified by coupling advanced sensors and a director fire control system with the modified F-15B flight control system. Specific flight test performance goals listed by Meyer, Crispino and Lyons<sup>29</sup> were:

##### **AA Gunnery**

- 3:1 increase in expected hits;
- 2:1 reduction in time to first firing opportunity;
- 4:1 increase in number and duration of firing opportunities; and
- demonstration of a greatly increased employment envelope in high angle off/high line-of-sight rate encounters.

##### **AG Gunnery and Bombing**

- 10:1 increase in survivability against linear predictor AAA;
- 2:1 increase in weapon delivery accuracy of the IFFC system over similar non-wings-level manual manoeuvres for the baseline vehicle; and
- retention of present wings-level weapon delivery accuracy while performing preplanned non-wings-level manoeuvres.

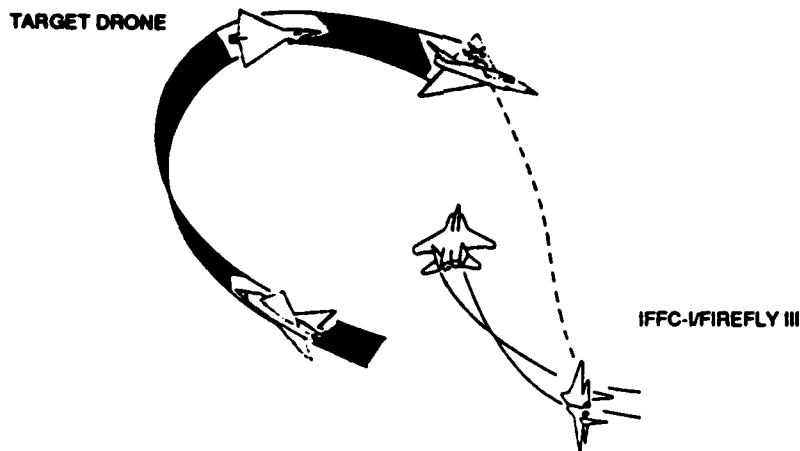
Results from flight testing in the early 1980s confirmed the effectiveness of the system, showing that unguided bombs could be delivered during turning manoeuvres, without any significant loss in accuracy over wings-level release conditions<sup>1</sup>.

Another demonstration exercised the IFFC Air-to-Air Gunnery mode against a PQM-102 Delta Dagger target drone. The successful attack was carried out from the near impossible front quarter (130° difference in heading). The drone was travelling at 420 kt in a 4 g turn to the right while the F-15B was at 400 kt in a 3.3 g turn also to the right (see Figure 8). The pilot opened fire at 1770 m from the target and ceased fire two seconds later at 1160 m, hitting the drone with approximately 20 percent of the rounds fired<sup>30</sup>.

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**FIGURE 8. IFFC air-to-air engagement geometry (from Ref. 30)**

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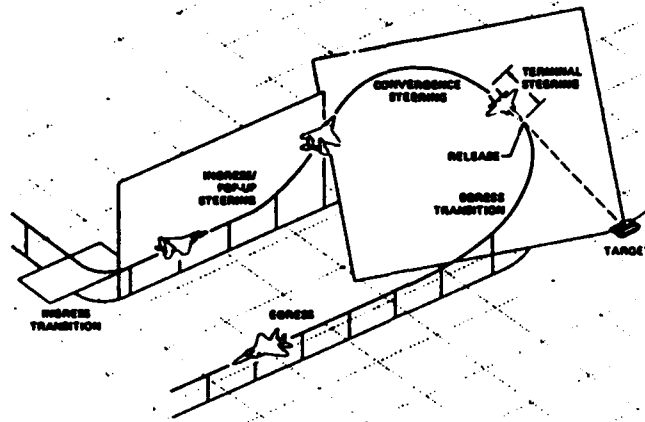
### IFWC

Concepts developed through the IFFC-1/FIREFLY III program were extended under the USAF sponsored study of 'Integrated Flight/Weapon Control' (IFWC), which was carried out in the early 1980s. IFWC focused on assessing the advantages that IFFC technology could offer to the delivery of guided weapons and dispenser munitions. Weapon delivery concepts were developed and assessed using 'pilot in the loop' simulation facilities<sup>31</sup>.

As a baseline for this study, the F-15 aircraft was selected along with two air-to-air weapons, AIM-9L Sidewinder and AIM-7F Sparrow, and two air-to-ground weapons, AGM-65 Maverick and TMD Tactical Munitions Dispenser. Simulation results showed that pilots would readily accept and use both IFFC air-to-air gunnery assistance and automated curvilinear TMD deliveries because of the increased accuracy and reduced pilot workload evident with those two options.

**FIGURE 9. IFWC air-to-surface delivery (from Ref. 31)**

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IFWC delivery of air-to-surface guided missiles was also considered to be beneficial, particularly under conditions of low visibility. Automatic steering options provided by IFWC were not considered to be necessary or useful for air-to-air missile engagements, and IFWC transitions from missile to gun control were found to be unacceptable. Later IFWC programs, such as AFTI F-16 and ICAAS, address issues raised by the IFWC study in more detail.

#### **AFTI F-16**

The Advanced Fighter Technology Integration (AFTI) program was initiated in 1974 by the USAF Flight Dynamics Laboratory to provide a means for developing new technologies so that they may be more easily incorporated into future fighter systems. The technologies to be examined were categorised into three 'technology sets' (Figure 10) so that they could be implemented on test-bed aircraft for experimentation<sup>32</sup>.

**FIGURE 10. AFTI initial technology sets**

| Set I   | Set II   | Set III   |
|---|--|---|
| F-16 Testbed Aircraft   | F-111 Testbed Aircraft   | Undefined Testbed   |
| <ul style="list-style-type: none"> <li>• Direct force</li> <li>• Advanced aerodynamics/structure</li> <li>• Coupled fire/flight control</li> <li>• Weapon line pointing</li> <li>• Pilot-Vehicle Interface</li> <li>• Digital flight management and control system</li> </ul> | <ul style="list-style-type: none"> <li>• Variable camber</li> <li>• Advanced structure</li> <li>• Active flight control</li> <li>• Gust load alleviation</li> <li>• Creepless supercritical airfoil</li> </ul> | <ul style="list-style-type: none"> <li>• Integrated weapons carriage</li> <li>• HI OC aerodynamics</li> <li>• Favourable aerodynamic interferences</li> <li>• Supersonic cruise fighter technology</li> </ul> |

The AFTI/F-16 advanced development program (Technology Set I) became a joint USAF, USN and NASA effort in which 357 test flights were conducted between 1981 and 1987 to accomplish initial program objectives. Phase one of the program, 1981 to 1983, saw the implementation of the Digital Flight Control System (DFCS). Phase two, 1983 to 1987, focused on the development of an Automated Maneuvering Attack System (AMAS), thus extending integrated fire/flight control technology beyond the work done under IFFC-I/FIREFLY III.

Modifications made to the F-16A testbed aircraft (Figure 11) include:

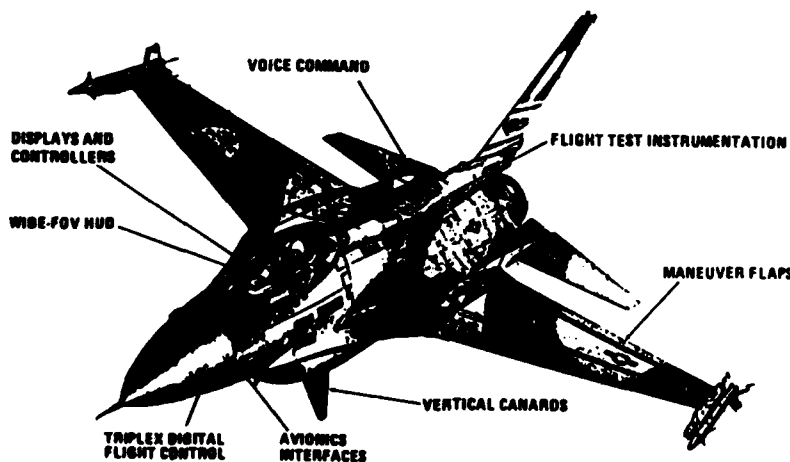
- vertical canards taken from the YF-16 Control Configured Vehicle (CCV) program which had earlier conducted investigations into decoupled flight modes<sup>33</sup>;
- sensor tracker pod conformally mounted on the right wing root and containing both FLIR and YAG laser ranging equipment;
- triplex digital flight control enabling implementation of the integration and automation technologies;
- 360° radar altimeter usable at all roll attitudes and essential for aggressive automatic low level flying\*;

\*. One example of aggressive automatic low level flying is the AMAS automated egress mode, where one-half second after bomb release, the aircraft would roll to 135° of bank and apply up to 5 g in a pull-down manoeuvre to acquire the pre-selected egress altitude. The AMAS would then execute a 5 g level turn at egress altitude until disengaged.

### 3. INTEGRATED CONTROL DEVELOPMENTS

- voice interactive avionics used to augment the Hands On Throttle And Stick (HOTAS) concept, providing voice control over radio, navigational systems, cockpit displays, data entry and a status query system;
- helmet mounted sights used for both off-boresight target designation and reverse cueing where the location of the target is fed back to the pilot through his/her helmet mounted display; and
- manoeuvre flaps which utilised the standard F-16A leading and trailing edge flaps as aerodynamic motivators to improve performance and enhance pitch control during combat manoeuvres.

**FIGURE 11. AFTI/F-16 testbed aircraft**



The DFCS enabled the realisation of task-tailored (multi-mode) flight control laws. Thus, flight control laws on the AFTI F-16 were made mode switchable to provide the best handling for various air-to-air and air-to-surface scenarios. A wide range of flight-control laws were flight tested, from the conventional to fully decoupled flight modes (decoupling airframe translation and rotation movements). In general, it was found that a blended combination of direct force and conventional control laws provided optimum handling for most tasks.

#### **AMAS**

The AMAS phase integrated the specially tailored flight control system with fire control, Helmet Mounted Sight (HMS) and FLIR/laser pod to automate bombing and gunnery tasks. System details are well described in Ref. 34.

The AMAS could demand up to 180° per second roll rates, any roll attitude, between 1 g and 5 g in pitch, and up to 1 g of direct sideforce (in one particular mode) to attack a designated target automatically. Without exception, however, pilots disliked any level of automatically commanded flat turn and so the only decoupled flight mode to be used by AMAS was reduced to a pilot selectable option<sup>35</sup>. Flight tests demonstrated low level (200 feet above ground level) delivery of unguided bombs, whilst manoeuvring horizontally at up to 5.2 g, without any significant degradation in bombing accuracy over a standard F-16A wings-level approach. Operation of the coupled air-to-air gunnery system was also demonstrated. In-flight fusing was implemented, demonstrating real-time control over the pattern and dispersal of submunitions during both curvilinear and wings-level attacks<sup>2</sup>.

Pilot acceptance of the system was an important factor in the success of the AMAS project. A flight proven Ground Collision Avoidance System (GCAS) and an independent System Wide Integrity Management (SWIM) monitor were indispensable features which provided pilots with an acceptable level of confidence for aggressive automated low level attacks<sup>35</sup>.

#### **CAS/BAI**

After achieving many of the initial AFTI goals, the AFTI/F-16 was used in a follow-on program to optimise and integrate technologies for Close Air Support (CAS) and Battlefield Air Interdiction (BAI) missions. Program goals were to improve first pass target acquisition, improve aircraft survivability, and to develop the capability for covert night and bad-weather operations. Three phases were scheduled to develop and integrate the appropriate technologies.

In phase one, the use of an Automatic Target Hand-off System (ATHS) data link was demonstrated<sup>36</sup> where target data (location and type etc.) were digitally transmitted to the AFTI aircraft to achieve single pass target acquisition. Once the target information has been received (e.g. from ground based forces), the target can be displayed on the digital map, the HUD, and the pilot's helmet mounted sight. In a similar fashion, the pilot can locate alternative targets and transmit them through the ATHS so that other aircraft can engage them. This technology, which is currently being installed in US Army AH-64 helicopters, has lent itself to a number of advanced bomb delivery strategies, including spotter-shooter scenarios where one high speed spotter aircraft transmits detailed target data to shooter aircraft following a more covert flight path.



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### 3. INTEGRATED CONTROL DEVELOPMENTS

Phases two and three, which have carried on into the early 1990s, were planned to develop the CAS/BAI capabilities further through improving the AMAS to operate in all-terrain (as opposed to relatively flat terrain); through development of more covert Terrain Following, Terrain Avoidance and Threat Avoidance (TF/TA<sup>2</sup>) systems; and through development of the capability to operate at night and under adverse weather conditions.

#### ICAAS

The Integrated Control and Avionics for Air Superiority (ICAAS) program, initiated by the USAF in 1987, aims to develop, integrate, and demonstrate technologies which will enable friendly tactical fighter aircraft to kill and survive when outnumbered as much as four to one by enemy aircraft<sup>37</sup>. In particular, the studies have focused on beyond-visual-range combat with effective transition to close in combat, integration of attack/defensive engagement options, and automation of tasks selected by the pilot. ICAAS places emphasis on systems integration as a technology necessary for the development of synergism by accounting for complex interactions between attack and flight management functions, weapons and sensors.

ICAAS assists the pilot through five functional areas:

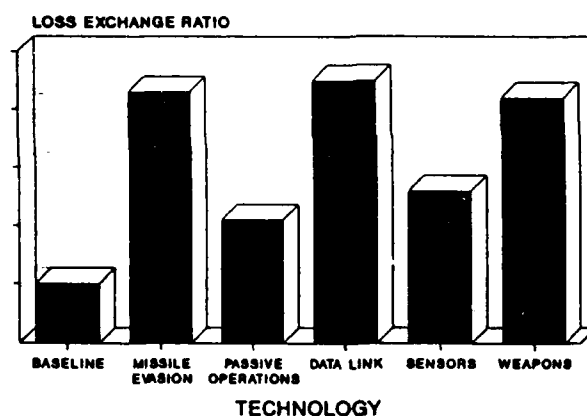
- **Attack Management** - automatically controls and integrates onboard sensors with information received over the in-flight data link from other flight members to provide the pilot with enhanced situational awareness. Weapon (fire) control information is provided on the basis of the fused data.
- **Tactics** - evaluates the situation and recommends tactics according to a rule-based approach. Different tactics are presented to the pilot with an associated 'figure of merit'. After the pilot selects an option, coordinated assignments are allocated to each flight member. The scenario is continuously monitored in order to be reactive to the actions of the enemy aircraft.
- **Attack Guidance** - provides flight trajectory information for attacking enemy aircraft while maximising self survival. Missile-aircraft engagement options are computer modelled at high speed to provide recommendations on the most appropriate flight path.

### 3. INTEGRATED CONTROL DEVELOPMENTS

- **Defensive Assets Manager** - becomes active when the aircraft becomes threatened by an enemy missile. An extensive database is used to assist the pilot with a list of prioritised evasion options (both manoeuvres and counter-measures).
- **Performance Monitor** - assists the pilot in achieving the best possible performance from the aircraft.

Extensive non-piloted and piloted simulations have been carried out to identify technologies and tactics which would most contribute to the ICAAS objectives, using flight testing as a means of 'spot-check' validation. Early sensitivity studies showed that the loss exchange ratio (or number of enemy losses divided by the number of friendly losses) could be greatly increased by further development of missile evasion algorithms, data links for improved situation awareness, and long range weapon technologies (Figure 12)<sup>38</sup>.

**FIGURE 12. Technology benefit study (from Ref. 38)**



Although actual results from the program have not been made available (because of security restrictions), it would appear that those associated with the program are enthusiastic about the benefits that ICAAS technologies offer.

#### 3.3 Enabling Technologies

Many of the research and development programs previously discussed had as their primary objective the development and integration of enabling technologies with a view to incorporating new capabilities into current and future aircraft. The following technologies have been identified as contributing to the development of integrated control applications.

#### Digital Systems

The integrated management of aircraft subsystems tends to produce quite complex control laws with a large number of observable quantities and controllable system variables. This may correspond to a large system state matrix. According to Hecht<sup>39</sup>, computer workload tends to increase proportionately more than the squared size of the matrix. Hence, without the rapid expansion in aircraft computer processing capability witnessed over the last two decades, implementation of such complex control laws would not be feasible. Furthermore, digital systems facilitate the sharing of data between subsystems, and provide the flexibility for adapting new control algorithms relatively quickly.

#### New Design Methods

New aircraft designs will benefit most where control is functionally integrated from the outset as opposed to integration when design is almost complete. To foster this attitude, the USAF initiated the Design Methods for Integrated Control Systems (DMICS) study in the early 1980s, directed primarily at developing IFPC design methodology. An alternative program with similar goals, Integrated Methodology for Propulsion and Airframe Control (IMPAC), has been developed by NASA taking into account DMICS developments<sup>40</sup>.

The VAAC program discussed in section 3.1 is also expected to develop design methods which are suitable for functionally integrated control systems.

#### Multivariable Control Theory

Until recently, flight control systems were designed using classical techniques (root locus, Nyquist etc.) which are ideally suited to single-input-single-output systems. The application of classical design techniques to multiple-input-multiple-output systems frequently results in overly conservative designs which do not take full advantage of system capabilities. Despite this, there has been considerable reluctance to make use of modern control theories which inherently manage multivariable systems more efficiently. This is partly due to a demonstrated lack of robustness in early modern control designs. (A 'robust' system implies a controller which will perform adequately despite the presence of uncertainties and noise in the controlled system.) The control research community addressed the issue of increasing modern control robustness during the 1980s.

Hill<sup>41</sup> and Smith<sup>9</sup> have reviewed the development of advanced control law design techniques in some detail. Of the numerous control strategies developed during the 1980s, it would appear that  $H^\infty$  optimal control theory, a progression of the Linear Quadratic Gaussian (LQG) method, has matured to the point where it is considered a viable candidate for flight control applications<sup>42,43</sup>.

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### 3. INTEGRATED CONTROL DEVELOPMENTS

Control laws developed for the S/MTD IFPC aircraft may be used as an example of current multivariable control law technology. As documented by Moorhouse and Kisslinger<sup>22</sup>, all S/MTD contractors were "strongly encouraged to use multivariable control theory" during design. The experiment highlighted two points:

- Purely conventional control systems did not benefit from using multivariable control theory, while classical design techniques provided better insight into the system.
- For complex and/or unconventional systems, a combined classical and multivariable design approach gave the best trade-off between complexity and performance.

#### Digital Simulation

Extensive simulation modelling of functionally integrated control systems has become a mandatory part of the development cycle<sup>11, 17, 19, 31, 32</sup>. For integrated control simulation to be successful, subsystem models need to be developed to similar levels of sophistication<sup>10</sup>. Simulation has been used in the research programs discussed, as a cost effective means of investigating new integrated control concepts, and for providing insight into otherwise unfamiliar system interactions.

#### More Effectors

Fuselage pointing, expanded flight envelopes, VTOL/STOVL applications, and new flight modes all benefit from additional control effectors apart from the conventional aerodynamic surfaces (such as rudder, ailerons etc). In addition to the usual control effectors, the following have been used in integrated control research projects to attain some improvement over the original configuration:

- thrust vectoring for V/STOL, expanded envelope, high alpha control, decreased manoeuvre drag and improved control over airspeed;
- canards, acting together or differentially, as with the AFTI-F16 and S/MTD F-15, to improve fuselage pointing and handling characteristics;
- variable camber wings, including either manoeuvre flaps or flexible wings which adjust wing camber to optimise the lifting performance of the wing throughout manoeuvres;
- nose blowing, which is used to maintain attitude control at high angles-of-attack by modulating the forebody vortex system to effect yawing moments on the aircraft; and
- variable geometry inlets, which are used to ensure that airflow to the propulsion system is of a suitable quality for all flight conditions.

#### **More Sensor Data**

Both the amount of data available and the number of sensors carried within military aircraft have been steadily increasing over the years. Digital data internetting (for example ICAAS), more complex subsystem designs such as the F100-PW-229 turbine engine, and improved sensor tracker systems, including FLIR, laser ranging etc. all provide additional data which has both driven and facilitated the development of integrated control applications.

#### **Improved PVI**

Pilots generally cannot absorb all the data available to them regarding the state of aircraft subsystems and the battlefield environment. Pilot inputs to aircraft systems are becoming increasingly complex (consider the AFTI F-16 which had ten switches on the sidestick controller and eight more on the throttle, some of which had more than one function<sup>15</sup>). For these reasons, the pilot-vehicle interface (PVI) has been the subject of considerable attention in recent years. Helmet mounted displays/sights<sup>16</sup>, voice recognition/generation systems<sup>17</sup>, advanced displays, and new inceptors (controls)<sup>18</sup> are options being explored to improve the PVI.

Data fusion<sup>19</sup> and artificial intelligence techniques (for example the Pilot's Associate program<sup>20</sup>) have been identified as technologies most likely to assist pilots in maintaining an acceptable level of situational awareness while performing complex tasks.

#### **Digital Terrain Databases**

Onboard digital terrain databases have enabled technologies such as Terrain Following/Terrain Avoidance (TF/TA), Terrain Reference Navigation (TRN) (such as the Tactical Terrain Matching (TACTERM) system developed by ARL), and advanced Ground Collision Avoidance Systems (GCAS)<sup>21</sup>. These systems, in turn, have become key technologies for integrated control developments, which include automated low level flying.

#### **Trajectory Generation**

Technology for the generation of desirable aircraft trajectories, directed toward increasing survivability or mission effectiveness, is rapidly reaching maturity due to advances in onboard computing power over recent years. Trajectory generation technology can be used for advanced combat guidance, as with the ICAAS program<sup>17</sup>, obtaining maximum benefit from finite resources (for example, minimising fuel required to get to a given flight state<sup>12</sup>), and facilitating TF/TA<sup>2</sup> applications. Halpern<sup>49</sup> provided a comprehensive review of TF/TA literature.

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#### 4. SPECULATION ON THE FUTURE APPLICATION OF INTEGRATED CONTROL WITHIN AIRCRAFT

As highlighted by Hill<sup>41</sup>, the generation of desirable aircraft trajectories for fulfilling mission goals is an enabling technology for integrated control applications. The Defence Science and Technology Organisation has undertaken several research activities incorporating trajectory generation technology<sup>50,51,52</sup>.

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#### 4. SPECULATION ON THE FUTURE APPLICATION OF INTEGRATED CONTROL WITHIN AIRCRAFT

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Although it is impossible to predict exactly which technologies will find most favour in tomorrow's military aircraft, we can speculate upon likely developments by examining future aircraft requirements, and the technologies which show promise for meeting those requirements.

##### **What can be said about aircraft of the future ?**

The growing cost of owning and operating military aircraft has led many defence forces to purchase fewer units, placing increased emphasis on the ability of an aircraft to perform its mission successfully and survive. It is reasonable to expect that this trend will continue for some time to come. Even today, expensive advanced technology solutions are contributing toward the development of so-called 'Silver Bullet' ideologies. The 'Silver Bullet' represents a minimum number of performance optimised aircraft which may be used to defeat numerically superior, but technologically inferior, threats.

Well designed platforms are increasingly expected to perform more than one type of combat mission. Furthermore, as there is a general trend towards increased inter-Service cooperation<sup>53</sup>, we might expect aircraft to operate in more complex battlefield scenarios than are currently practiced.

System complexity is likely to be the most significant factor which will limit the application of integrated control technology to future aircraft design. Because of the increased complexity, flight qualification of functionally integrated control systems, and qualification of new systems to be integrated into the aircraft, will probably become more difficult<sup>54,55</sup>.

##### **Which technologies are likely to be sought after ?**

Looking at the above, it would seem that aircraft of tomorrow will require increased mission performance capabilities, increased ability to survive and return, improved flight availability, and means of assisting the pilot in accomplishing missions, despite general trends which increase the number of complex tasks.

Research programs during the last two decades have demonstrated that integrated control technology has a major part to play in achieving these goals. In the author's opinion, the technologies most likely to be transitioned into service in the near term include:

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## 5. CONCLUDING REMARKS

- multi-mode flight control laws;
- Self-Repairing Flight Control System technologies;
- Integrated Flight and Fire Control targeting technologies; and
- Integrated Flight and Propulsion Control HIDEDEC Performance Seeking Control technologies.

The overall trend has been towards increased automation of tasks which either enhance the capability of the aircraft, or reduce pilot workload demand. An example of this is fly-by-wire technology, which has enabled features such as carefree handling and multi-mode flight control.

If this automation trend continues, perhaps layered integrated control is an option for the future. For example, the lowest level of integration might consist of subsystem couplings like those developed through the HIDEDEC and FIREFLY projects. A higher level of integration may see the development of 'vehicle management systems' with improved PVI to assist the pilot in obtaining the best overall performance from the aircraft (subsystems) as a whole. Integration of the battlefield, or alternatively, integration of several aircraft to work together as one system, would be the top level of integration (such as is being investigated in part by the ICAAS project).

### **When are these technologies likely to be implemented ?**

Some of the integrated control technologies discussed have already been implemented through mid-life upgrades and design modifications to aircraft currently in service (for example the HIDEDEC IFPC technologies). Other developments, especially those which require major hardware design modifications such as thrust vectoring, should gradually become commonplace as new aircraft designs are brought into service. An example of this would be the US designed F-22 fighter aircraft for which the SRFCs program had a specific mandate to provide advanced flight control strategies.

Several integrated control research programs have taken their developments through to flight testing with the explicit objective of proving the technologies so that they may be considered for current and future aircraft. The demonstrated benefits of using integrated control technology imply that aircraft with digital systems are likely to take advantage of these developments during the next ten to twenty years.

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## 5. CONCLUDING REMARKS

Research programs addressing integration of flight control with other aircraft subsystems have been discussed. The range of technologies being examined by those programs demonstrate that integrated control, by its nature, encompasses numerous technology disciplines.

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## 6. SUGGESTIONS FOR FURTHER WORK

Flight testing and simulation studies have, in many cases, verified that aircraft incorporating integrated control technology will have significant improvements in performance and operability over otherwise similar aircraft. Projects which explore the integration of sensor data from sources external to the aircraft (through digital data networking) also show considerable promise.

The primary disadvantage associated with functionally integrated control is an increase in system design complexity. In practice, the level of integration between aircraft subsystems will be dependent upon a trade off between system design complexity and mission performance.

Overall, more complex aircraft subsystems and increasingly large amounts of data to be processed onboard the aircraft imply that integrated control will remain a key technology for modern military flight control systems. Aircraft which employ digital flight control systems, such as the F/A-18 used by the RAAF, are particularly well positioned to take advantage of certain integrated control technology developments.

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## 6. SUGGESTIONS FOR FURTHER WORK

For the reasons discussed in the body of this report, integrated control issues have become major driving forces behind the development of modern aircraft control technology. Aircraft integrated control technology seems to have a low profile within the Australian aerospace community, despite considerable investment in a number of the enabling technologies. The following suggestions represent basic and enabling research activities directed at developing Australian research and development infrastructure.

- A watching brief on integrated control technology developments should be maintained, with an emphasis on developments which are likely to be applicable to the Australian Defence Force (ADF).
- Most integrated control publications to date have dealt with benefits of integrated control based on the requirements of forces substantially different from the ADF. In preparation for future aircraft purchases and mid-life upgrades, a study could be carried out to determine which integrated control technologies would be expected to provide the greatest pay-off for ADF operational requirements. Lower life cycle costs and improved operational effectiveness are two issues which should be examined in such a study.
- An in-depth understanding of integrated control issues can probably only be attained by actually undertaking an integrated control development exercise. It has been noted by Hill<sup>41</sup> and others<sup>5</sup> that the F/A-18 is an ideal candidate for the implementation of Integrated Flight and Fire Control modes. A design investigation could be performed using



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## **ACKNOWLEDGEMENTS**

air-to-air Integrated Flight and Fire Control specifications as a means of becoming familiar with integrated control issues of relevance to the F/A-18 aircraft. Simulations would be used to refine and evaluate performance of proposed systems.

## **ACKNOWLEDGEMENTS**

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- AIAA** Proceedings of the American Institute of Aeronautics and Astronautics
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G.J. Simpkin

DSTO-GD-0013

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